

LIDAR Remote Sensing Concepts

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1) New Millennium Program

1.1 Introduction

The primary goal of the NASA New Millennium Program (NMP) is to develop technology for use on future operational missions. The Program consists of two thrust areas, one oriented towards developing technologies for Deep Space Probes and one oriented towards developing technology for Earth Observing Probes. Each thrust area intends to fly several technology demonstrator spacecraft designated DS-X and EO-X respectively where X is the mission number. Each mission has an ~\$100 million cap on total mission cost. The EO-1 mission has been selected and is under development. The instrument discussed here was submitted by NASA MSFC as a potential candidate for the EO-2 or EO-3 missions due to launch in 2001 and late 2002 or early 2003 respectively. This report summarises and follows the format of the material provided to NMP.

1.2 Mission Objectives

1.2.1 Science:

To profile horizontal wind speed in the troposphere such that the measurement requirements identified by the NOAA Working Group on Space-Based Lidar Winds [1] are met. These requirements were recently adopted by the NOAA/DOD/NASA NPOESS Integrated Program Office as the (currently) unaccommodated EDR for winds and have subsequently been adopted, with some modification, by the New Millennium Program. To further the attainment of these science goals, the purpose of this instrument is to:

- Obtain accurate, unbiased line of sight (LOS) wind velocity estimates from the PBL, clouds, and regions of high backscatter in the mid-troposphere.
- Demonstrate the combination of various LOS velocity perspectives into horizontal velocity estimates.
- Assimilate horizontal wind measurements (and possibly LOS measurements) and demonstrate NWP and climate change benefit.
- Demonstrate accurate assignment of cloud top and bottom heights.

1.2.2 Technical:

To demonstrate the successful operation of a coherent Doppler lidar for the measurement of wind such that sufficient confidence is developed in the technique to enable the development and deployment of a wind sensor on NPOESS. The optimisation of the NPOESS wind sensor will also be enabled through analysis of this mission.

1.3 Mission Concept

The instrument will utilise Doppler analysis of coherently detected backscatter from entrained aerosols and cloud particles in the troposphere. The instrument design is based on a series of studies collectively known as AEOLUS (Figure (1.1)) that were conducted at NASA Marshall Space Flight Center.

The AEOLUS concept called for an instrument that could be mounted to any available platform and this concept was carried forward into this preliminary concept design for NMP. The obvious benefit of this approach is that any platform that satisfies the basic accommodation requirements can be utilised.

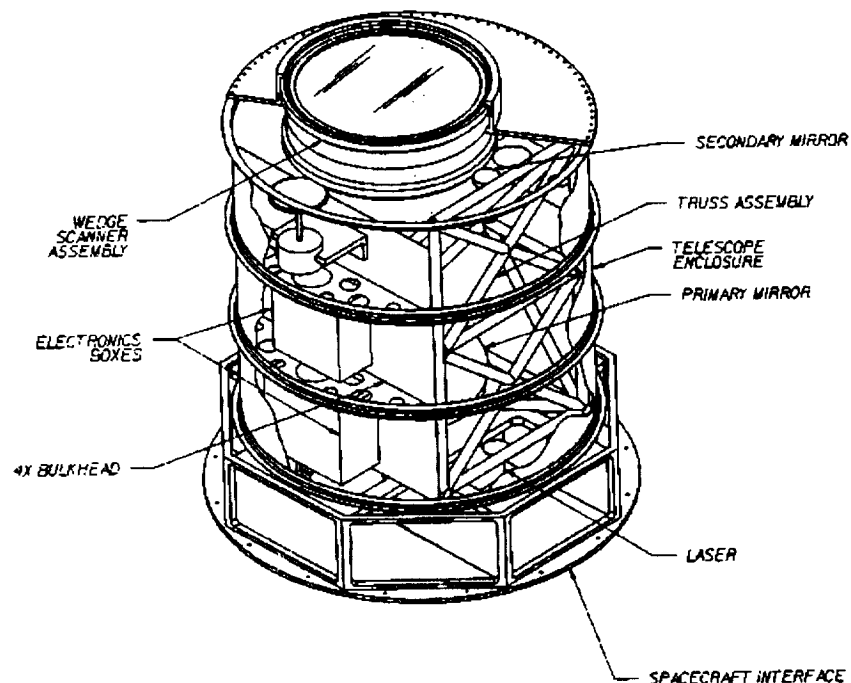


Figure (1.1) A schematic of the AEOLUS instrument from which the NMP design was derived.

A block diagram of the instrument subsystem is shown in Figure (1.2).

1.4 Description of Technology

A solid state transmit laser produces a 0.5 J, 0.2-0.5 μ s long single mode pulse at a nominal wavelength of 2 μ m and a nominal PRF of 10 Hz. The transmitted beam is expanded to a collimated beam by a 0.5 m diameter nadir-looking 3-element off-axis telescope and deflected 30 deg. from nadir by a rotating Si wedge. The wedge produces an elliptical beam transmitted into the atmosphere resulting in an effective telescope aperture of 0.46 m. A diffractive/holographic element

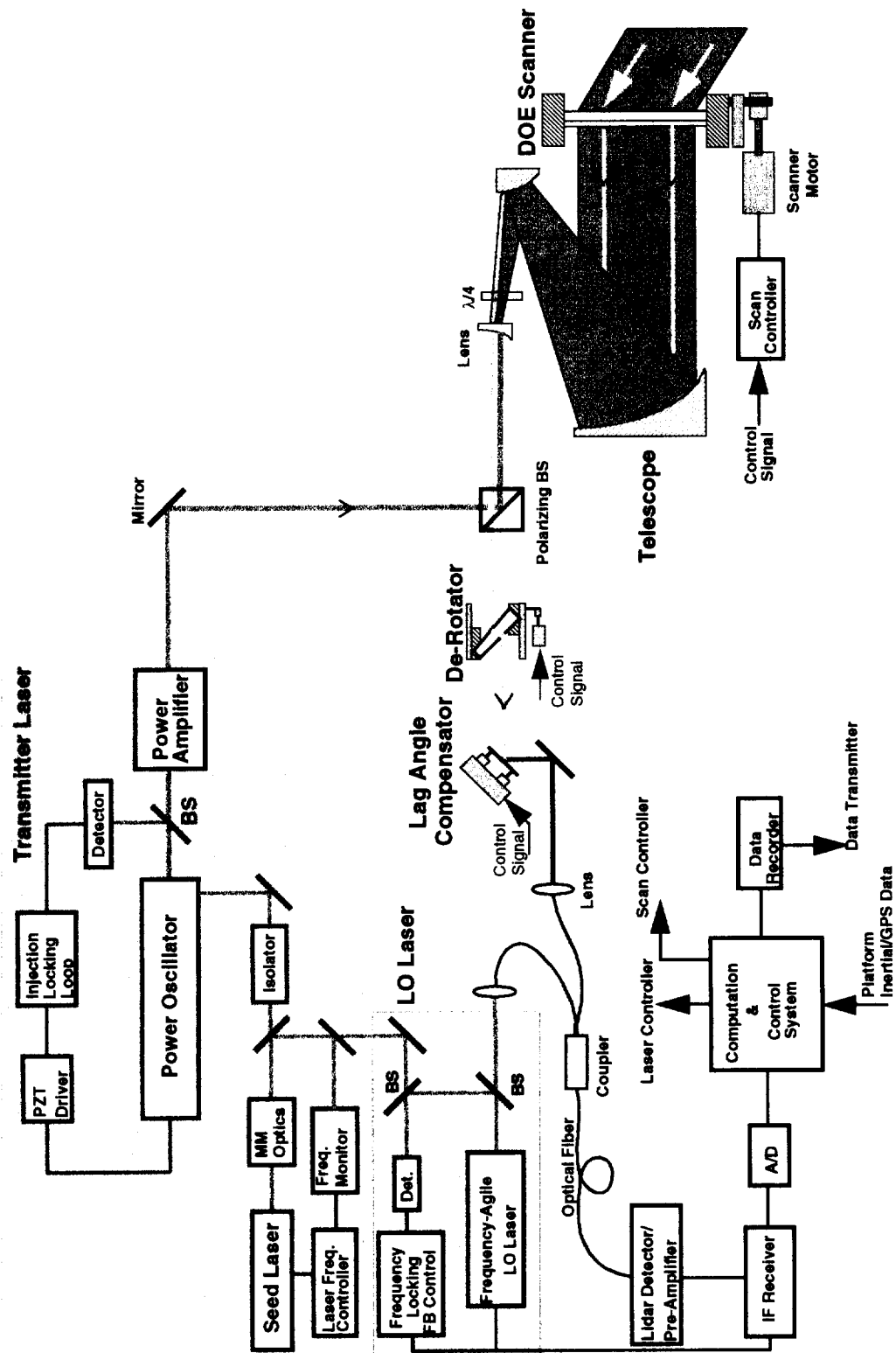


Figure (1.2) Instrument schematic showing the major subsystems.[2]

would be used in place of the wedge (with a considerable mass saving) if the technology matures sufficiently. As the beam is transmitted through the atmosphere, a small fraction is backscattered by aerosols and clouds. The backscattered signal is frequency shifted due to the relative velocity of the target and the spacecraft.

The backscattered signal is collected by the telescope and routed to the room temperature InGaAs signal detector using a Wang geometry optical receiver [3][4]. At the detector, the signal is mixed with an optical local oscillator (LO) signal. The local oscillator frequency is tuned to remove most of the Doppler shift due to the spacecraft motion. The electronic portion of the receiver uses a tunable electronic local oscillator to remove frequency shifts due components of the earth's rotational velocity seen by the instrument and to provide fine adjustment for potential errors in the optical local oscillator frequency. The signal is then split into I and Q components and digitised. The digitised signal is stored together with appropriate housekeeping and health and status data and at an appropriate time downloaded to the ground through the spacecraft supplied data link.

Finally, on the ground, the data is run through a velocity estimator to convert the signal frequency into a line of sight velocity vector. Velocity vectors from individual shots at different perspectives can be combined to produce vector(s) representative of the wind field.

1.5 Mission Benefits

1.5.1 Near-term:

This initial technology demonstrator mission will provide the scientific community with a significant amount of data to enable the optimisation of the impact that an operational wind lidar will have on climate change research and weather prediction.

1.5.2 Long-term:

An operational wind lidar will improve long term weather forecasting and this can result in cost savings for many industries (e.g. farming) that depend on weather forecasts. The instrument has potential for improved disaster prediction with a resultant reduction in deaths and injuries or of unnecessary evacuations. A review of the economic benefits of a space based wind lidar is contained in a report by J.J. Cordes.[5]

1.6 Justification for Space Flight

Coherent lidar has a long and varied history of providing atmospheric wind velocity measurements from the ground and from airplanes. The need for the measurement of winds from space has been well documented [6] but a coherent lidar has been perceived as technologically complex and risky to fly directly as an operational science instrument. The NMP provides an ideal opportunity to validate the technology from space and thereby deliver the technology for one of the significant unmet atmospheric parameters into the hands of the science and operational forecasting communities.

1.7 Instrument Characteristics

Table (1.1) summarises the basic instrument characteristics requested by the New Millennium Program.

Characteristic		Value	Comments
Spacecraft	Type	Any	Will consider any platform satisfying accommodation requirements
	Orbit type	No preference	
	Orbit altitude	300 - 400 km	Prefer low orbit to maximise SNR
	Orbit inclination	as close to 90 as possible	Maximise coverage of earth's surface
Laser	material	Ho:YLF or Th,Ho:YLF	
	wavelength	2.02 or 2.06 μm	
	pulse energy	500 mJ	Maximise within spacecraft power and available technology constraints
	pulse width	200 - 500 ns	Must be shorter than minimum range gate.
	L.O. tuning range	± 4 GHz	to remove Doppler shift induced by spacecraft motion wrt target
Optical	Diameter	0.5 m	
	Scanning type	30 deg conical	Provides coverage, biperspective wind views
	Scanner	Si wedge	Will use HOE/DOE if wavefront/efficiency requirements can be satisfied
Mass		358	Includes 20 % contingency and some contingency at the subsystem level
Power		625/289/162	Operational/ warm-up/ standby; includes 20% contingency
Data	Peak Rate	~6 MB/s	See text for assumptions
	Volume	~50 MB/day	Assuming 10% duty cycle
Overall envelope		1.22 (D) x 1.35 (L) m^3	Cylindrical shape
Technology Readiness Level		3/4	

Table (1.1) Instrument Characteristics requested by NMP.

1.8 Data Plan

1.8.1 Strategy:

Two basic mission profiles are being considered for an operational instrument, the first assumes continuous data collection and rapid provision of that data to the Numerical Weather Prediction (NWP) community at all times. The second uses hindcasting [7] and requires operation ~10% of an orbit but at times specified by the NWP community. At this time it is not clear how large the resources available to a lidar on the converged DOD/NOAA platform will be.

The first option uses a nominally 10 Hz laser prf to provide a reasonable shot pattern density (see Figure (A.9) in Appendix A for typical shot patterns) throughout an entire orbit. This requires considerable resources from the platform as the instrument is continuously consuming ~650 W and producing raw data at the rate of ~6 MB/s or ~500GB/day.

The second operational scenario recognises two basic facts. The first is that for a significant fraction of the time, the output from the current global climate models is generally adequate. The second is that an active remote sensor such as a coherent Doppler lidar consumes a lot of spacecraft resources (power) and is thus expensive to support. Recognising these facts the science community is investigating the feasibility of using hindcasting to determine the optimum locations for collecting data with a coherent Doppler lidar. This technique relies on running numerical weather prediction models and looking at divergences in the output results from different models (or the same model with slightly perturbed input conditions). These divergences are indicative of a breakdown in the model and can frequently be traced back to some set of localised starting conditions. In an operational sense, when a region of inadequate atmospheric data has been identified, an orbiting lidar could be programmed to collect data in that region during the next several passes over the region. These regions are likely to be associated with unstable atmospheric conditions and thus need to be well sampled in order to extract useful wind data. This leads to the requirement of a higher PRF from the laser and the 20 Hz currently identified is probably close to a bottom limit on the acceptable PRF. It is currently estimated that there will be several such regions each orbit leading to the lidar being operational ~10% of the time. This results in a significant reduction in the average power consumption for the lidar - although the peak power consumption during operation will increase.

It should be noted that at this time there is insufficient evidence to assess the value of the hindcasting approach and a series of Observing System Simulation Experiments (OSSEs) needs to be conducted by the NWP community in order to provide suitable data for evaluating the potential of the technique.

The mission proposed to the New Millennium Program requested an orbit duty cycle of ~10% as it was felt that this was high enough to provide sufficient data volume to validate the concept of using lidars to generate meaningful wind data but low enough to not have the platform data link become a significant cost driver. In a final operational system the data recorded would be subject to compression techniques and it is felt that the lidar data (particularly from higher altitudes) will be amenable to some simple but effective (lossless) compression schemes.

1.8.1.1 On Orbit:

Operation required for ~ 10% of each mission cycle; occasional real-time downlink for system diagnostics at ~6 Mb/s (assuming no data compression).

1.8.1.2 Calibration/Validation Plan:

Intercomparison against land-based and airborne wind lidars. At least two overflights of a land-based station desired. Intercepts with airborne instruments and NSCAT are also anticipated.

The NPOESS IPO has expressed interest in supporting calibration and validation of any demonstration mission. NOAA has also expressed interest in supporting calibration and validation activities as well as the possibility of existing support from within NASA Code Y. It was anticipated that the Marshall DAAC (which has subsequently been closed) would have been made available for data processing.

1.8.1.3 Post-Mission:

One of the goals of the mission would be to demonstrate the feasibility of the timely delivery of data to the NWP community. In this respect considerable work will be carried out prior to mission completion. However it is anticipated that 8 months of post-processing and reconciliation with data from the calibration and validation program will be required. A statement of goals met/not met would be provided 12 months from end of mission.

1.9 Accommodation Requirements

In addition to the information given in Table (1.1) the control, stability, knowledge and data requirements listed in Table (1.2) - (1.5) were also provided to the NMP.

The data in Table (1.2) - (1.5) assume a 300 km orbit height. It should be noted that the transmitter/receiver boresight alignment requirement in Table (1.2) is a stability requirement over the signal round trip time (ie 2.3 ms) only and is not equivalent to a "Hubble" type staring specification where the boresight must be effectively held for some considerable time period.

Specification	Value	Driving Requirement	Comments
S/C horiz. velocity	15 m/s	Budget for received signal spectrum shift	
Laser nadir angle at S/C	0.1 deg (360 arcsec)	Budget for received signal spectrum shift	GLAS ~90 arcsec
Laser azimuth angle at S/C	0.1 deg (360 arcsec)	Budget for received signal spectrum shift	GLAS ~90 arcsec
XMTR/RECR boresight alignment over echo time	3.2 μ rad (0.671 arcsec) over 2.3 ms	3 dB SNR loss	GLAS < 2 arcsec over 1 s

Table (1.2) Control/stability requirements provided to NMP.

Specification	Value	Driving Requirement	Comments
S/C horiz. velocity	0.6 m/s	0.3 m/s LOS velocity error	
S/C vert. velocity	0.35 m/s	0.3 m/s LOS velocity error	
Nadir angle at S/C	45.5 μ rad (9.4 arcsec)	0.3 m/s LOS velocity error	GLAS ~ 5 arcsec
Azimuth angle at S/C	74.1 μ rad (15.3 arcsec)	0.3 m/s LOS velocity error	GLAS ~ 5 arcsec
S/C altitude above local earth surface	50 m	Max. 50 m target height error	
Round trip time of light	0.4 μ s	Max. 50 m target height error	
Freq. diff. XMTR at t=0 to LO at t= 2.3 ms	300 kHz	0.3 m/s LOS velocity error	
Local horiz. direction relative to a perfect sphere	~ 4 deg.	0.3 m/s error in converting LOS velocity to horiz. velocity; 100 m/s max. horiz. velocity	

Table (1.3) Knowledge requirements provided to NMP.

Parameter	Value	Notes
nominal maximum wind velocity any direction	± 100 m/s	Permits observation of some jets. This is not the bandwidth for the purpose of calculating SNR.
error in nadir angle	+/- 0.1 degs	Increasing the nadir angle increases the signal capture bandwidth required.
transmitter/lo frequency offset error	10 MHz	Accounts for failure to exactly tune the optical local oscillator to the correct frequency.

Table (1.4) Assumptions used in assessing the data requirements.

Parameter	Value	Notes
Sampling rate above Nyquist	1.1X	
Digitiser resolution	12 bit	Could possibly manage with 10 bit (reduces data storage) but restricts dynamic range available.
Aerosol target altitude range	0 - 20 km	
Guard band range	1 km	This represents additional digitising time outside of the 0-20 km window listed above and ensures capture of data in the event of a timing error.
Electronic Receiver type	Complex	Splitting the electronic receiver lowers the bandwidth required from the A/D converters but increases the number of A/D converters required.
Duty cycle	10%	Based on the proposed data plan for this demonstration mission.
Ancillary data	240 bits	A nominal allocation of 20x12 bit words for ancillary data is included in the data requirement estimates.
Data compression	None	Worst case scenario - in reality there is likely to be potential for considerable data compression.

Table (1.4) Assumptions used in assessing the data requirements.

Parameter	Value	Notes
Peak sample rate	149 Msamples/s	A simple analysis without accounting for the frequency errors listed in Table (1.4) reduces this to ~100 Msamples/s.
Digitisation time for each pulse	163.2 μ s	This is the time for the optical pulse to travel through the atmospheric sample to the ground and back out again.
Data collected on one shot	583,242 bits	
Data collected in one orbit/ one day	3.2 GB/ 50.4 GB	10% duty cycle

Table (1.5) Data requirements

1.10 Sensitivity Analysis

An analysis of the performance of the instrument was carried out using the UAH/NASA MSFC lidar simulation model. Appendix A contains screen shot prints of the analysis carried out for this particular mission.

The velocity estimator used for coherent Doppler lidar has a probability density function (PDF) associated with it [8] This PDF expresses the likelihood that the velocity measured is the true wind velocity and not a random noise spike. The performance of coherent Doppler lidar is generally characterised by the aerosol backscatter value at which the probability of the velocity estimate being closely grouped near the true velocity value is 0.5.

Given this situation then, on a single shot basis the instrument will have a worst case backscatter sensitivity (for a mid-latitude summer atmosphere) of $\sim 1 \times 10^{-7}/(\text{m-sr})$ in the boundary layer with a 250 m vertical resolution range gate. In the troposphere the instrument will have a single shot backscatter sensitivity of $\sim 1 \times 10^{-8}/(\text{m-sr})$ for a 2 km vertical resolution range gate. These backscatter estimates include allowances for 6dB of SNR loss due to instrument degradation.

Without these performance degradation margins the (ideal) performance of the instrument on a single shot basis is $\sim 3 \times 10^{-8}/(\text{m-sr})$ in the boundary layer and $\sim 3 \times 10^{-9}/(\text{m-sr})$ in the troposphere. The use of shot averaging [9] over n shots can produce an $\sim \sqrt{n}$ or better reduction in the minimum detectable backscatter value. The instrument contribution to the velocity error will be $< 1 \text{ m/s}$ on a single shot.

It should be noted that for backscatter values less than those listed above, the instrument will still produce a velocity estimate but the likelihood that the estimate will be grouped near the correct value will be less than 0.5.

Nevertheless, the combination of velocity estimates from over a grid cell (100 km x 100 km in the boundary layer and 500 km x 500 km in the mid/upper troposphere) can still extract the mean wind velocity in the cell (under certain conditions) by looking at the distribution of the individual velocity estimates.

1.11 Status

After submission of the instrument design, a request was made from the NMP as to the feasibility of cutting the mission further and they were informed of an ongoing effort to attempt to fit a coherent lidar within Hitchhiker canisters. The status of this design is covered next.

2) Hitchhiker Instrument Design

2.1 Introduction

A series of conceptual designs for fitting a coherent Doppler lidar into Hitchhiker canisters was conducted. A Hitchhiker canister is a standardised cylinder for STS (space shuttle) payloads provided by the Shuttle Small Payloads Project Office at Goddard Space Flight Center. The canisters can be pressurised and are available either sealed or with a motorised opening door. Table (2.1) summarises the basic parameters of these canisters, detailed specifications are provided in the

Parameter	Value	Parameter	Value
Interior length	31.25" (28.25" for user)	Power	Nominally two 28V DC 10 Amp lines
Interior diameter	20" (19.75" for user)	Max. total power	1600 W (HH-C - 8 customers) 1300 W (HH-S 3 customers)
User mass	200lbs (160lbs for motorised door canister)	Max. total energy	10kWh/day (HH-C) 4kWh/day (HH-S)
Misc interfaces	Four (three for motorised lid can) 28V bi-level or pulse commands (10mA max) for driving relays	Data	Asynchronous 1200 baud downlink 1-1400 kb/s downlink (split payloads) 50Mb/s downlink by request
	IRIG-B format serial time code One pulse/minute square wave signal 3 channels for temperature sensors (sealed cans only) Analog 0-5V channel, converted to 8 bit values, 15 Hz sample rate.	Command	Asynchronous 1200 baud uplink channel

Table (2.1) Basic specifications for a Hitchhiker canister.

Hitchhiker Customer Accommodation and Requirements Specification (CARS) documentation available from GSFC.[10] It should be noted that the Hitchhiker platform provides no thermal interfaces, all instrument generated heat must be radiated by the instrument. Figure (2.1) shows both sealed and open-lid canisters together with the GSFC supplied Hitchhiker support avionics mounted on the side of the STS payload bay (Hitchhiker-S). The canisters can also be mounted on a cross-bay bridge structure (Hitchhiker-C). Programmatic requirements are that at least 24 months prior to flight, the customer delivers complete documentation on the payload to GSFC and the flight hardware must be delivered to GSFC ~6 months prior to flight.

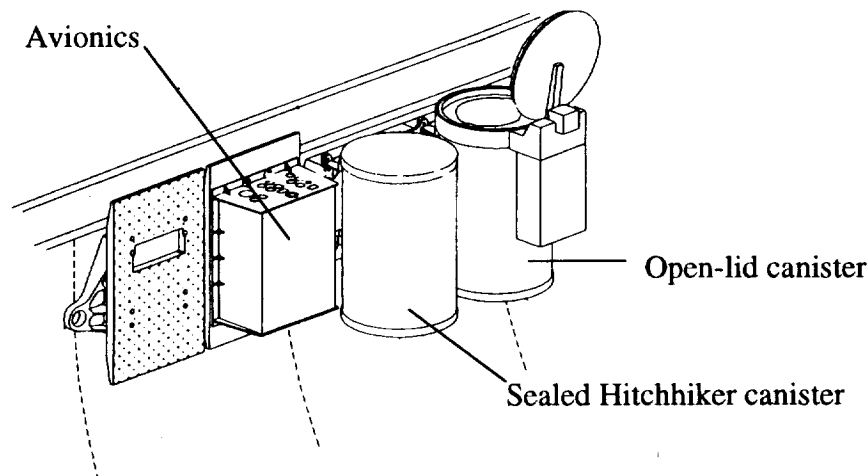


Figure (2.1) Representation of Hitchhiker canister payloads mounted to STS wall.

2.2 Design Concepts

A preliminary design was developed to assess the feasibility of using an existing 100 mJ, 6 Hz 2 μ m flashlamp pumped laser, 25 cm diameter telescope [11] and Si wedge scan element available at MSFC. The design concept followed that of the Shuttle Laser Altimeter (SLA) and attempted to use two Hitchhiker canisters, one for the lasers and optics and one for the electronics and controls. The design concentrated on ensuring that all the laser and optical components would fit in one canister. A summary of the preliminary mass properties for this instrument is given in Table (2.2). This table (and the others associated with this design) are not complete because it quickly became clear that there were several problems associated with accommodating the flashlamp pumped laser. These included, but were not limited to, a power draw in excess of what the Hitchhiker carrier could provide, an associated heat dissipation problem and the need to redesign the laser resonator to permit packing within the constraints of a Hitchhiker canister volume. Of these three concerns, the power and thermal constraints were the most problematic.

Table (2.3) lists the preliminary estimate for power consumption among the various subsystems of the instrument. The pulsed laser power estimate is based on a 6 Hz pulse rate with 185 J of energy deposited into the flashlamps for 100 mJ of single mode Q-switched output energy. From the table it is clear that the inefficiency of the flashlamp laser drives the power consumption outside of that available from the Hitchhiker platform. Further compounding the problem is the fact that the lidar is an earth-observing instrument. This means that during operation the STS bay is oriented towards the earth and consequently the ability to reject heat is severely limited. For this instrument, essentially all of the power consumed in Table (2.3) has to be radiated as heat.

This analysis showed that the existing 6 Hz flashlamp pumped laser could not be used as the laser source for a Hitchhiker packaged instrument and the possibility of using a diode pumped laser was investigated. The subsequent conceptual design used conduction cooled diodes to pump the laser and Figure (2.2) shows the difference in power consumption between the flashlamp pumped

laser design and the conduction-cooled-diode pumped laser design. The use of conduction-cooled

MASS	Can 1 (lbs)	Can 2 (lbs)	Total (lbs)
Lasers	31.0	75.1	106.1
Local Oscillator	8.0	10.0	18.0
Master Oscillator	1.0	3.0	4.0
Pulsed Laser	22.0	62.1	84.1
Optical subsystem	129.5	35.0	164.4
Window	13.0	0.0	13.0
Scanner	76.5	20.0	96.4
Telescope	30.0	0.0	30.0
De-Rotator	5.0	5.0	10.0
Lag-angle compensator	0.0	10.0	10.0
Miscellaneous Optics	5.0	0.0	5.0
Electronics	0.0	64.0	64.0
Receiver	0.0	20.0	20.0
Computer	0.0	44.0	44.0
Thermal	20.5	5.0	25.5
Pump	2.5	0.0	2.5
Bypass Valve	18.0	0.0	18.0
Radiator	0.0	0.0	209.1
Controller	0.0	5.0	5.0
Misc. Cabling etc.	10.0	10.0	
Structure	32.0	20.0	52.0
Total (Cans)	223.0	209.1	432.0
Radiator			209.05
Max acceptable	160.0	200.0	

Table (2.2) Mass properties of the flashlamp pumped laser Hitchhiker instrument concept.
diodes enabled the elimination of the fluid loop required for the flashlamp pumped system and the

adoption of heat pipes for conducting the heat to the outside of the canister. Although the mass in

POWER	Can 1 Power (W)	Can 2 Power (W)	Total Power (W)
Lasers	1165.0	472.4	1637.4
Local Oscillator	16.0	14.0	30.0
Master Oscillator	9.0	5.0	14.0
Pulsed Laser	1140.0	453.4	1593.4
Optics	32.0	28.0	60.0
Window	0.0	0.0	0.0
Scanner	15.0	15.0	30.0
Telescope	0.0	0.0	0.0
De-Rotator	5.0	5.0	10.0
Lag-angle compensator	12.0	8.0	20.0
Miscellaneous Optics			0.0
Electronics	0.0	135.0	135.0
Receiver	0.0	40.0	40.0
Computer	0.0	95.0	95.0
Thermal	175.0	15.0	190.0
Pump	175.0	0.0	175.0
Bypass Valve	0.0	0.0	0.0
Radiator	0.0	0.0	0.0
Controller	0.0	15.0	15.0
Misc. Cabling etc.	10.0	10.0	
Structure			0.0
Total	1382.0	660.4	2042.4

Table (2.3) Power requirements of the flashlamp pumped laser Hitchhiker instrument concept.

can 1 was still over the 160 lbs outlined in the Hitchhiker documentation, a conversation with the Hitchhiker project office indicated that this did not necessarily prevent a mission from moving forward as there was considerable margin built into the Hitchhiker design. -A preliminary

Subsystem	Can 1	Can 2	
Local Oscillator	16.0	14.0	
Master Oscillator	9.0	5.0	
Slave Oscillator	90.3	62.9	
Window	0.0	0.0	
Scanner	15.0	15.0	
Telescope	0.0	0.0	
De-rotator	5.0	5.0	
Other Optics	12.0	8.0	
Receiver	0.0	40.0	
Computer	0.0	95.0	
Thermal	0.0	0.0	
Misc. cables, wiring etc.	10.0	10.0	
Structure	0.0	0.0	
Total	157.3	254.9	412.2
Goal			1000.0

Table (2.4) Power requirements of the conduction-cooled-diode pumped laser Hitchhiker instrument concept.

estimate of the instrument volume indicated that it would fit.

Subsystem	Can 1	Can 2	Other
Local Oscillator	8.0	10.0	
Master Oscillator	1.0	3.0	
Slave Oscillator	25.0	3?	
Window	13.0	0.0	
Scanner	76.5	20.0	
Telescope	30.0	0.0	
De-rotator	5.0	5.0	
Other Optics	5.0	10.0	

Table (2.5) Mass properties of the conduction-cooled-diode pumped laser Hitchhiker instrument concept.

Subsystem	Can 1	Can 2	Other
Receiver	0.0	20.0	
Computer	0.0	44.0	
Thermal	12.5	12.5	0.0
Misc. cables, wiring etc.	10.0	10.0	
Structure	32.0	20.0	
Total	218.0	157.5	0.0
Goal	160	200	

Table (2.5) Mass properties of the conduction-cooled-diode pumped laser Hitchhiker instrument concept.

For can 1 the ability to fit all the components within the canister envelope was verified from a preliminary engineering drawing of the packaging concept and for can 2 an initial estimate was made by totalling the known volume currently assigned to the can (5500 in^3) and comparing with the can volume (8600 in^3) - provided that there was considerable room left (as there was) it was not unreasonable to assume that the electronics could be repackaged as necessary to fit.

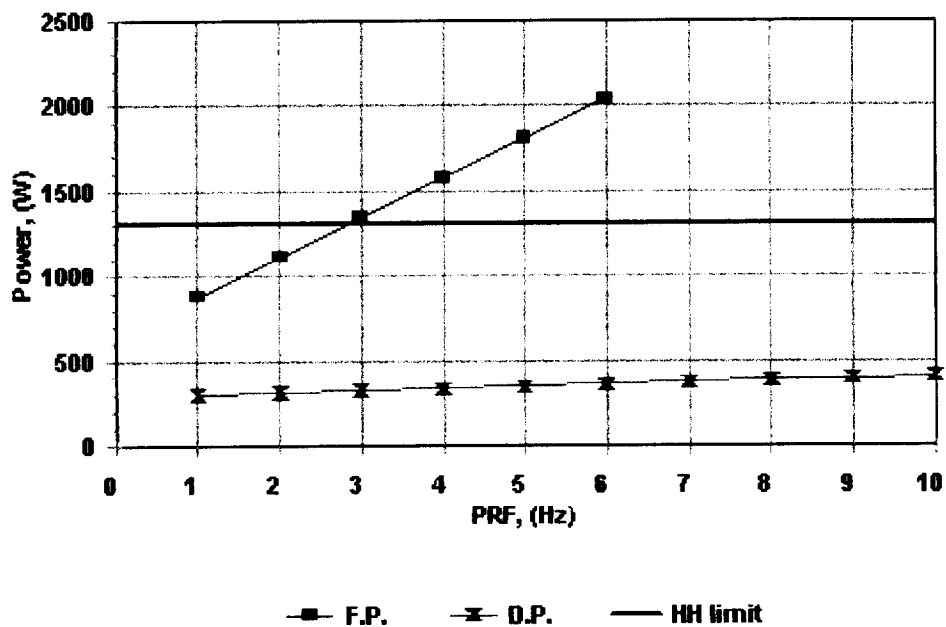


Figure (2.2) A comparison of the power consumption of the flashlamp pumped system (F.P.) and the diode pumped system (D.P.) as a function of laser prf. The red line represents the total simultaneous power available from a HH-S mount.

This preliminary conduction-cooled concept design was subsequently presented to NASA headquarters.

It should be noted that the design hinges upon the use of conduction-cooled-diodes to eliminate a bulky, inefficient fluid loop and that subsequent discussions with potential laser sources found a reluctance to commit to conduction-cooled-diodes. The thermal issues that this raises have not been adequately addressed by MSFC at the time of this report.

2.3 Performance Related Issues

This instrument is primarily a scaled down version of the one discussed in the previous section of this report. The primary difference from a sensitivity point of view arises from the reduced laser pulse energy and telescope diameter. One benefit of the decision to use a diode pumped laser was that this enabled the laser to be chosen with an optimum wavelength in terms of laser efficiency and atmospheric attenuation.

2.3.1 Wavelength selection

There are several issues to consider in choosing the laser wavelength:

- Laser efficiency

There are limited thermal dissipation capabilities within the Hitchhiker can and this will likely lead to a laser selection based on the most power efficient material.

- Atmospheric transmission at line center

The following table shows the two-way atmospheric transmission for some of the wavelengths discussed by laser suppliers. The transmission was calculated using Fascode for a 30 deg slant path from space to the ground using a tropical maritime atmosphere. This atmosphere was chosen as the most likely target for this instrument will be tropical marine aerosols. It can be seen that there is little difference between the two favoured laser hosts, Tm,Ho:YLF and Tm:YLuAG.

Two- way transmission			
Tm,Ho:YAG	Tm,Ho:YLF	Tm:YLuAG	Tm:YAG
2.091282 μm	2.065479 μm	2.021842 μm	2.012552
0.64	0.54	0.52	0.18

Table (2.6) Two way atmospheric transmission from 100 km to ground at a 30 degree nadir angle through a tropical marine atmosphere with 23 km visibility for four common 2 μm laser materials at line center.

- Change of atmospheric transmission with azimuth angle.

The relative velocity between the spacecraft and the earth results in a Doppler frequency shift of the return signal. The magnitude of the Doppler shift seen is a function of the azimuth angle and varies between $\sim \pm 4$ GHz of the laser centre frequency. Ideally we would like the atmospheric attenuation to be constant over the Doppler shift range so that the SNR is not dependent on the azimuth angle. With the exception of Tm:YAG, this is not a concern for the wavelengths under consideration. From Figure (2.3) - (2.6) we see that, except for Th:YAG, the atmospheric trans-

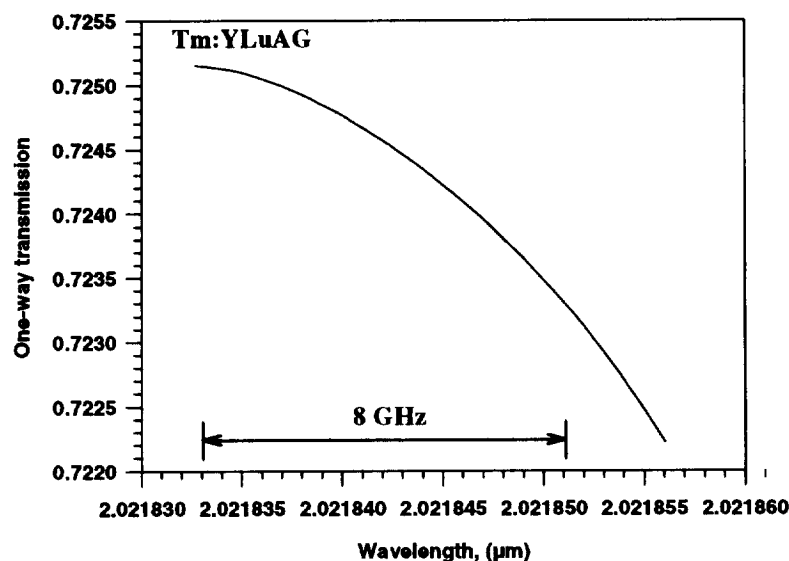


Figure (2.3) Atmospheric transmission from 100 km to the ground for Tm:YLuAG in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

mission only varies by small amounts over the bandwidth and the variation from material to material is insignificant. This means that, with the exception of Th:YAG, atmospheric attenuation is not a major driver on the selection of laser wavelength and the choice will be dominated by laser considerations ie primarily efficiency.

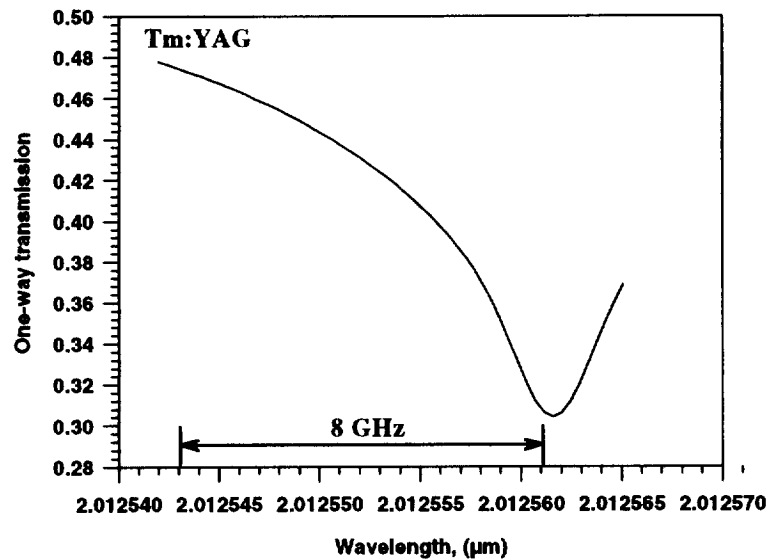


Figure (2.4) Atmospheric transmission from 100 km to the ground for Tm:YAG in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

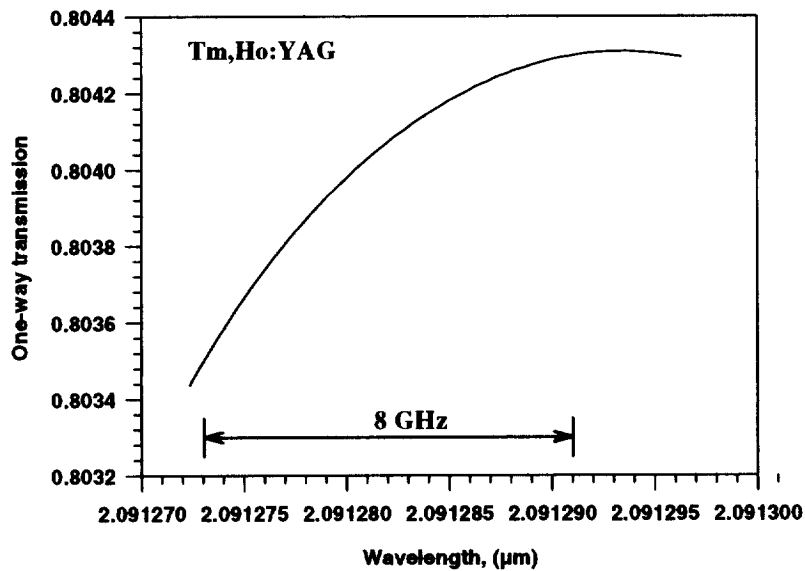


Figure (2.5) Atmospheric transmission from 100 km to the ground for Tm,Ho:YAG in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

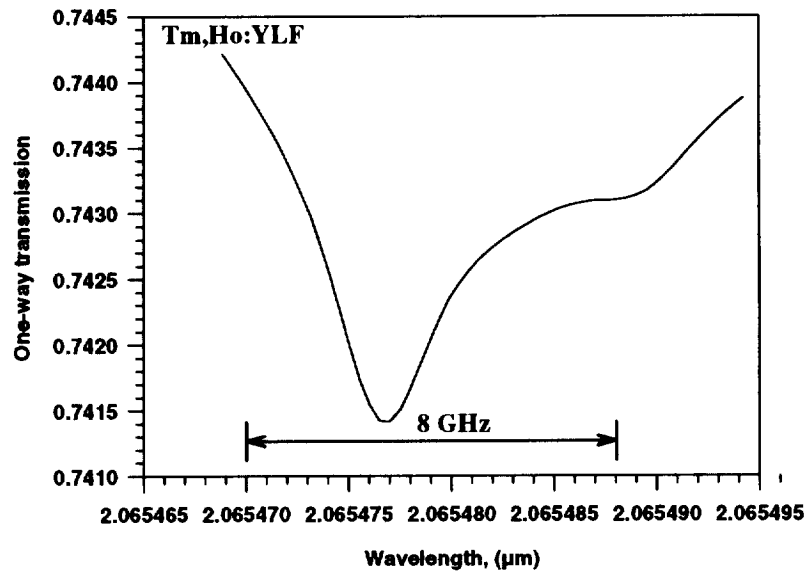


Figure (2.6) Atmospheric transmission from 100 km to the ground for Tm,Ho:YLF in a tropical maritime atmosphere with 23 km visibility and a 30 deg. nadir angle.

2.3.2 Instrument Sensitivity

As mentioned previously this instrument concept is a scaled down version of the one used for the NMP proposal and similar analyses were conducted to determine the instrument performance. Table (2.7) lists the instrument and orbit input parameters used by the model and Table (2.8) lists

LASER			ORBIT		
Wavelength	2.0654790	μm	Orbit height	300	km
Pulse energy	0.1	J	Inclination angle	50	deg
Pulse length	0.2	μs	Max. nadir angle at this height	72.75	deg
Duty cycle	1				
P.R.F.	10	Hz	RECEIVER/DETECTOR		
Additional spectral width (FWHM)	0	MHz	Type	Complex	
Gaussian spectral width	0.937	MHz	Geometry	Wang	
Frequency	145144277.91	MHz	Mixing efficiency	0.420	

Table (2.7) Parameters used to assess the Hitchhiker instrument performance.

Min. vertical range resolution	25.54	m	Heterodyne quantum efficiency	0.6	
			Detector truncation efficiency	1	
OPTICS			Detector shot noise efficiency	1	
Telescope diameter	0.25	m	Detector nonlinearity efficiency	1	
Nadir angle	30	deg	System efficiency	0.401	
Transmit intensity fraction	0.955		Total detection efficiency	0.071	
Transmit optics	0.8				
Receive optics	0.8		SCANNING		
Polarisation efficiency	0.97		Scan type	Wedge	
Wavefront aberration loss	0.95		Min. beam diameter	0.217	m
Receive/lo misalignment angle	6.765	μ rad	Effective beam diameter	0.233	m
Misalignment Loss	3.000	dB	Plot duration	1	mins
Misalignment efficiency	0.501		Telescope rotation rate	10	rpm
SYSTEM					
Margin for unexplained loss	0.5				

Table (2.7) Parameters used to assess the Hitchhiker instrument performance. the atmospheric, signal processing and other miscellaneous parameters used. Note that as the desired vertical range resolution changes, the signal processing parameters will also change.

TARGET			SIGNAL PROCESSING		
Atmospheric Model	Midlat Summer		Horiz. velocity search space	+/-20	m/s
Aerosol Model	Clear		LOS velocity search space	+/- 10.47	m/s
Aerosol altitude	0	m	Probability of a good estimate	0.5	
backscatter (λ)	5.212E-07	/(m-sr)	Line of sight range resolution	1173.710	m
Max. horizontal wind	+/-100	m/s	Observation time	7.830	μ s

Table (2.8) Atmospheric, signal processing and other miscellaneous parameters.

Horizontal wind velocity uncertainty	0	m/s	Effective time between samples	0.0493	μ s
Vertical wind velocity uncertainty	0	m/s	Effective digitisation frequency	20.278	MHz
Wind variance between shots	0	m/s	Effective no. samples / obs.	158.779	
Vertical range resolution	1000	m	Phi	4.895	
Target nadir angle	31.570	deg	Signal width	0.937	MHz
Line of sight range to this altitude	349.173	km	Omega	7.337	m/s
Coherence length	4.037	m	Sigmav/w	0.874	
One way Intensity Transmission	0.788		No. of shots/ wind estimate	1	
Maximum line of sight velocity	+/- 52.35	m/s	Bandwidth (wide band)	101.389	MHz
			Bandwidth (narrow band)	0.937	MHz
MISCELLANEOUS PARAMETERS			Bandwidth (search band)	20.278	MHz
Satellite velocity	7733.138	m/s	MLE row no.	32	
ground track velocity	7385.390	m/s			
Earth rotation velocity at equator	463.3360	m/s			
Nadir angle at ground	31.570	deg	RESULTS		
Slant range to ground	349.173	km	Wideband SNR	-22.100	dB
Time for one orbit	5420.452	s	Narrowband SNR	-1.758	dB
Swath radius (conical/wedge scan)	174.608	km	Searchband SNR	-15.110	dB
Optimum mirror flip time (line scan)	33.433	s	P(bad)	0.500	
Solid angle subtended at target	3.487E-13	sr	P(good)	0.500	

Table (2.8) Atmospheric, signal processing and other miscellaneous parameters.

The results from the model are summarised in Figure (2.7) - Figure (2.9). When looking at the

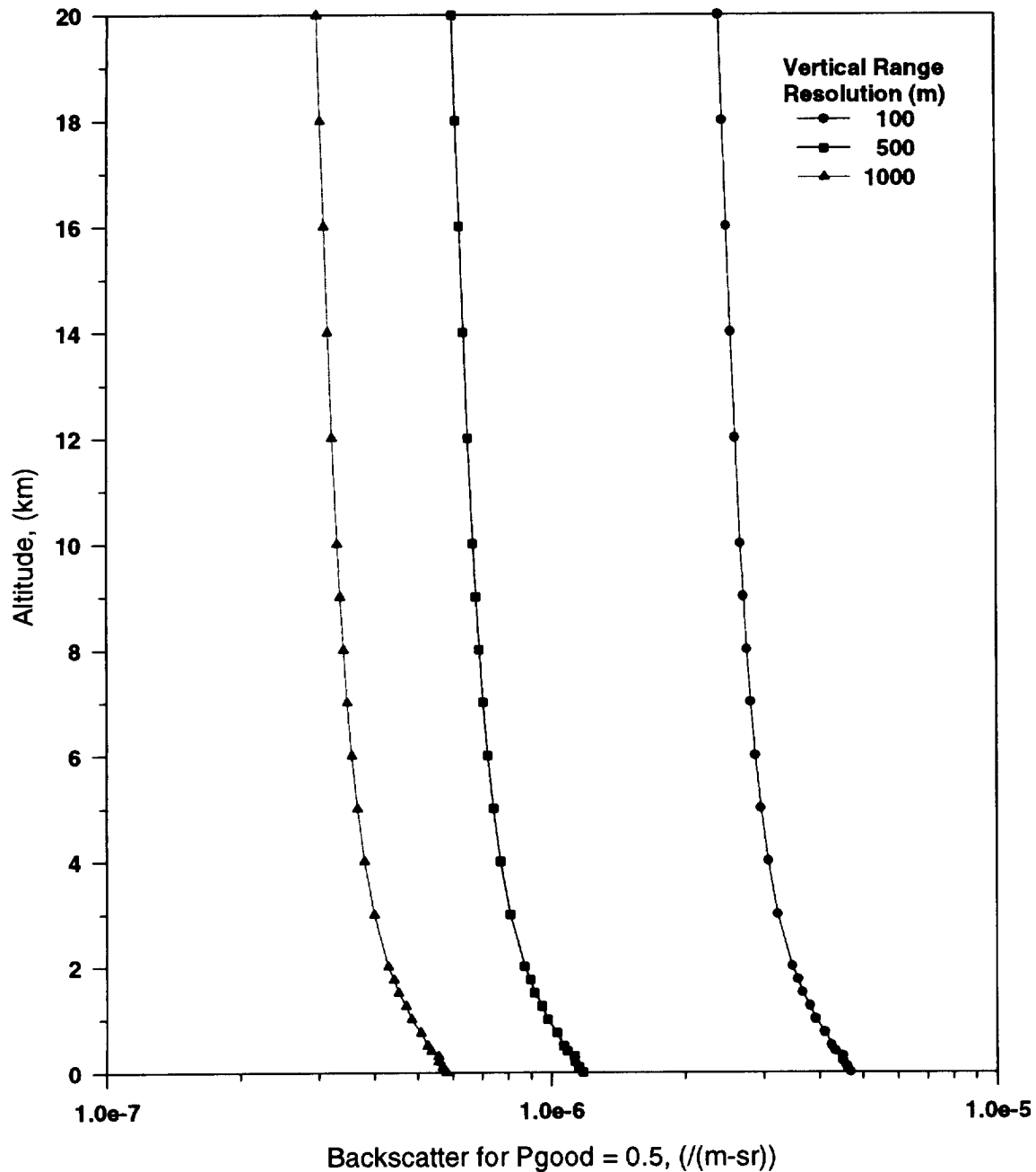


Figure (2.7) Single shot backscatter sensitivity as a function of altitude for range resolutions of 100 m, 500 m and 1000 m.

performance of the instrument by comparison with Figure (2.9) it must be remembered that this performance parameterisation carries at least 6dB of sensitivity degradation due to instrument effects. Additionally the instrument is likely to be run in a shot accumulation mode to improve the sensitivity.

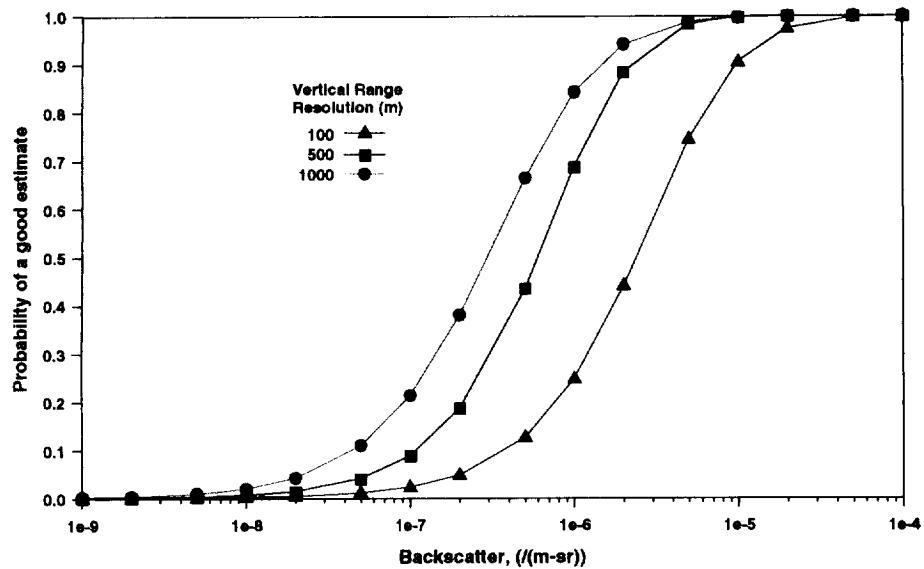


Figure (2.8) Performance of the maximum likelihood velocity estimator as a function of vertical range resolution and backscatter.

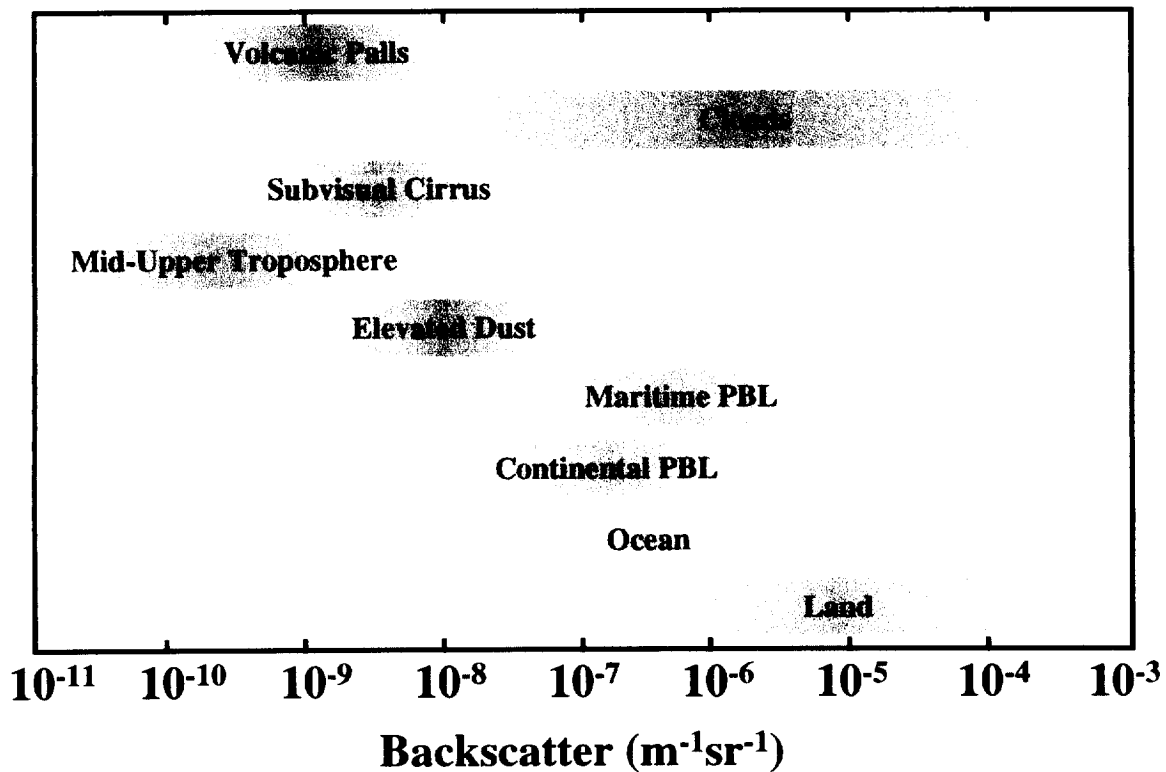


Figure (2.9) Natural Variability of $2\ \mu m$ Backscatter. [12]

2.4 Current Status

The instrument design is currently under further study to ensure that the design is feasible. From an engineering point of view the major tasks are to develop an adequate thermal design and to reduce the mass in the optics can. From the science point of view the major task is to extract the maximum benefit from a short duration mission with a limited sensitivity instrument.

3) References

[1] <http://eo.msfc.nasa.gov/general/require.html>

[2] Figure courtesy of Dr. Farzin Amzajerdian, Center for Applied Optics, University of Alabama in Huntsville, Huntsville, AL 35899.

[3] J.Y. Wang, Appl. Opt. 27, 4470-4474 (1988).

[4] B.J. Rye et al., Appl. Opt. 31 (15), 2891-2899 (1992).

[5] J.J. Cordes, "Economic Benefits and Costs of Developing and Deploying a space-based Wind Lidar", Final Report, D-9502, Contract No. 43AANW400223, National Weather Service, March 1995.

[6] see for example: W.E. Baker, G.D. Emmitt, F. Robertson, R.M. Atlas, J.E. Molinari, D.A. Bowdle, J. Paegle, M.J. Post, J.R. Anderson, A.C. Lorenc and J. McElroy, "Lidar-measured winds from space: A key component for weather and climate prediction", Bull. Amer. Meteor. Soc. 76(6), 869-888 (1995).

[7] Private Communication Dr. G.D. Emmitt, Simpson Weather Associates, Jan. (1997).

[8] see for example R.G. Frehlich et al., J. Atmos. & Oceanic Tech. 11(5), 1217-1230 (1994).

[9] R.G. Frehlich, J. Atmos. & Oceanic Tech. 13(3), 646-658 (1996).

[10] Goddard Space Flight Center, "Hitchhiker Customer Accommodations & Requirements Specifications", HHG-730-1503-07 (1994).

[11] Anees Ahmad, Farzin Amzajerdian, Chen Feng and Ye Li, "Design and fabrication of a compact lidar telescope", SPIE Vol. 2832, 34 - 44 (1996).

[12] Figure provided by Dr. Jeffry Rothermel, NASA MSFC and Mr. David Bowdle, University of Alabama in Huntsville, 23rd. April 1997.

Appendix A Model outputs for the NMP Parameters

Orbit	Laser	Optics	Receiver	Scanner	Target	dB Loss	Par.	EAP	BPg	S v. d.	X
Instrument Parameters											
LASER						ORBIT					
Wavelength 2.0654780 μ m						Orbit height 300 km					
Pulse energy 0.5 J						Inclination angle 90 deg					
Pulse length 0.5 ps						Max. nadir angle at this height 72.75220469 deg					
Duty cycle 1											
P.R.F. 10 Hz						RECEIVER/DETECTOR					
Additional spectral width (FWHM) 0 MHz						Type Complex					
Gaussian spectral width 0.3740 MHz						Geometry Wang					
Frequency 145144270 MHz						Mixing efficiency 0.420					
Min. vertical range resolution 63.3316216 m						Heterodyne quantum efficiency 0.5					
						Detector truncation efficiency 1					
						Detector shot noise efficiency 0.900					
						Detector nonlinearity efficiency 1					
						System efficiency 0.401					
						Total detection efficiency 0.065					
OPTICS						SCANNING					
Telescope diameter 0.5 m						Scan type Wedge					
Nadir angle 30 deg						Min. beam diameter 0.433612762 m					
Transmit intensity fraction 0.955						Effective beam diameter 0.46538243 m					
Transmit optics 0.8						Plot duration 1 mins					
Receive optics 0.8						Telescope rotation rate 10 rpm					
Polarisation efficiency 0.97						(Conical/wedge scan only)					
Wavefront aberration loss 0.95											
ReceiveAo misalignment angle 3.38262 prad											
Misalignment Loss 3.888 dB											
Misalignment efficiency 0.581											
SYSTEM											
Margin for unexplained loss 0.5											
Orbit Laser Optics Receiver Scanner Target dB Loss Par. EAP BPg S v. d. X NUM READY											

Figure (A.1) Instrument and orbit parameters

Orbit	Laser	Optics	Receiver	Scanner	Target	dB Loss	Par.	EAP	BPg	S v. d.	X
Target, Signal Processing and Other Miscellaneous Parameters											
TARGET						SIGNAL PROCESSING					
Atmospheric Model Midlet Summer						Horiz. velocity search space +/-10 m/s					
Aerosol Model Clear						LOS velocity search space +/- 5.24 m/s					
Aerosol altitude 500 m						Probability of a good estimate 0.5					
backscatter (lambda) 9.11E-08 (m-sr)						Line of sight range resolution 283.4187881 m					
Max. horizontal wind +/-100 m/s						Observation time 1.4575 ps					
Horizontal wind velocity uncertainty 0 m/s						Effective time between samples 0.0006 ps					
Vertical wind velocity uncertainty 0 m/s						Effective digitisation frequency 10.1301 MHz					
Wind variance between shots 0 m/s						Effective no. samples / obs. 14.7781					
Vertical range resolution 250 m						Phi 3.146					
Target nadir angle 31.5874 deg						Signal width 0.3740 MHz					
Line of sight range to this altitude 348.5858 km						Omega 0.5403 m/s					
Coherence length 4.206691 m						Signal/w 0.97726312					
One way Intensity Transmission 0.82116						No. of shots/ wind estimate 1					
Maximum line of sight velocity +/- 62.35 m/s						Bandwidth (wide band) 101.3812 MHz					
						Bandwidth (narrow band) 0.3740 MHz					
						Bandwidth (search band) 10.1301 MHz					
						MLE row no. 6					
OTHER PARAMETERS						RESULTS					
Satellite velocity 7733.136 m/s						Wideband SNR -16.717768 dB					
ground track velocity 7385.389 m/s						Narrowband SNR 7.8838189 dB					
Earth rotation velocity at equator 463.3367 m/s						Searchband SNR -8.7177682 dB					
Nadir angle at ground 31.5782 deg						P(bad) 0.489999999					
Slant range to ground 348.1727 km						P(good) 0.500000002					
Spot size on ground 1.244278 m						sigmaslos - instrument 0.3783 m/s					
Time for one orbit 5428.462 s						sigmaslos 0.5340 m/s					
Swath radius (conical/wedge scan) 174.301 km											
Optimum mirror flip time (line scan) 33.63325 s											
Solid angle subtended at target 1.4E-12 sr											
Orbit Laser Optics Receiver Scanner Target dB Loss Par. EAP BPg S v. d. X NUM READY											

Figure (A.2) Target, signal processing and other miscellaneous parameters.

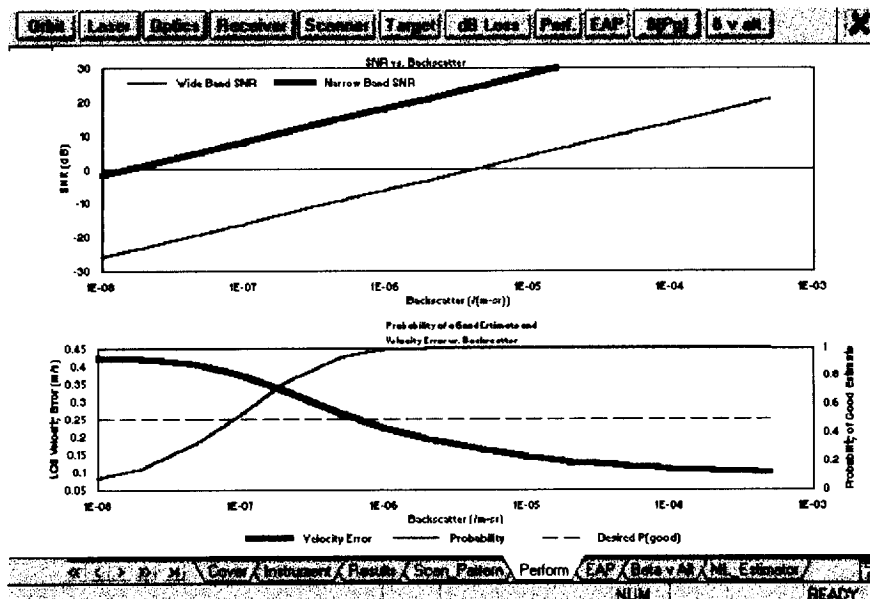


Figure (A.3) Signal to noise ratio and velocity estimator performance.

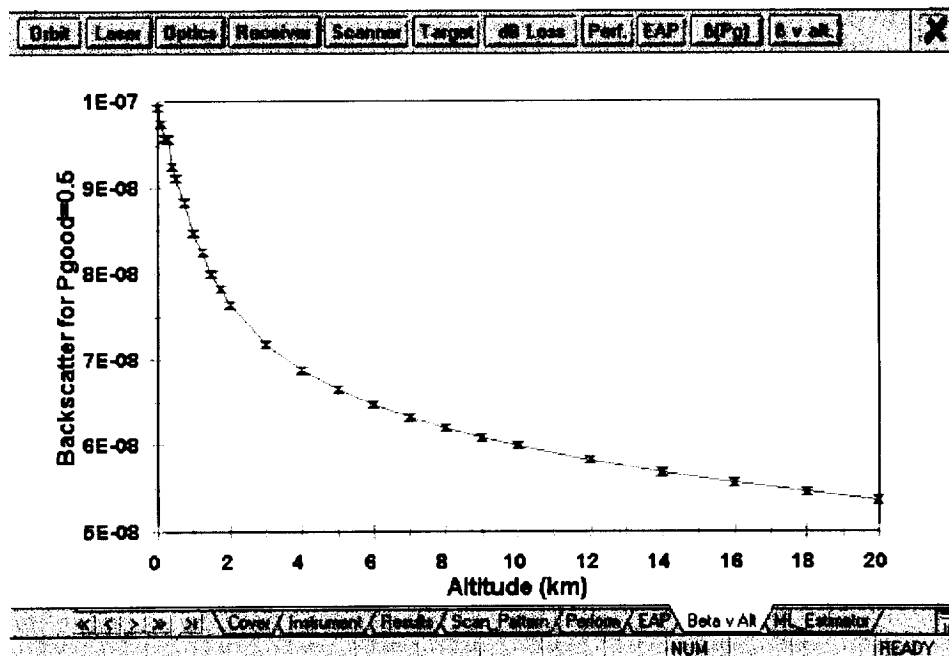


Figure (A.4) Sensitivity as a function of altitude for a 250 m range gate and a mid-latitude summer atmosphere.

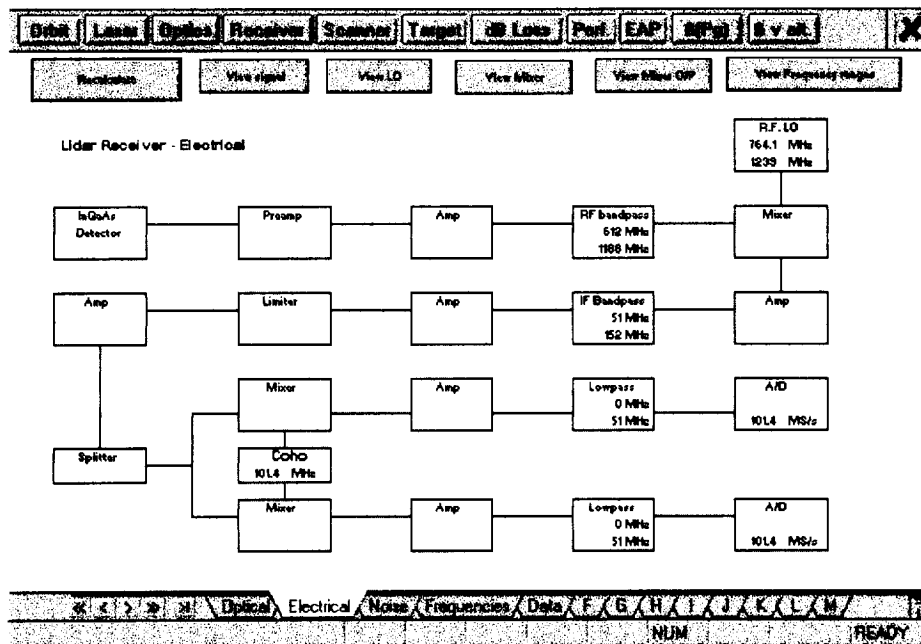


Figure (A.5) Receiver block diagram.

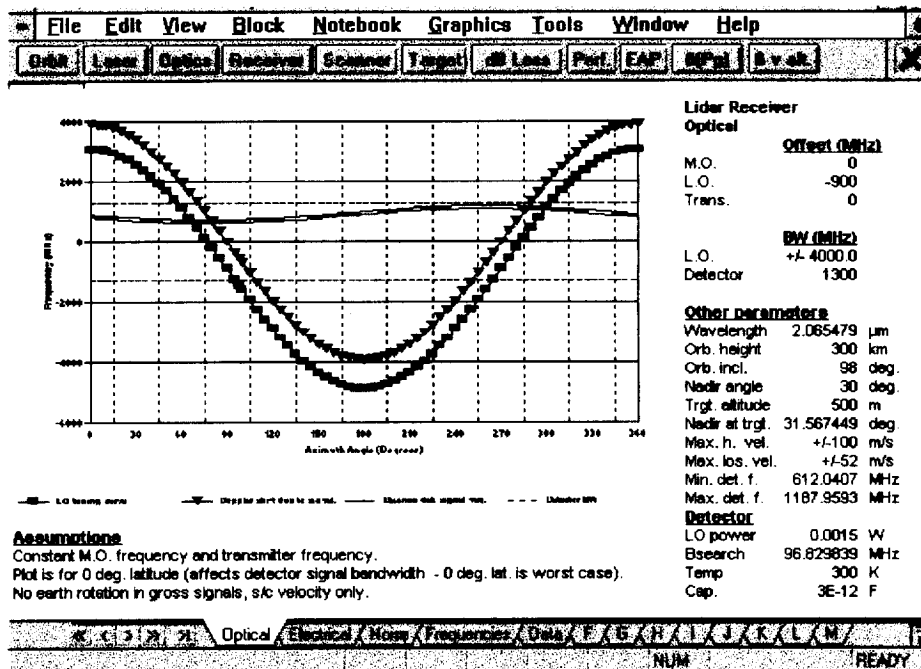


Figure (A.6) Optical frequencies as a function of azimuth angle.

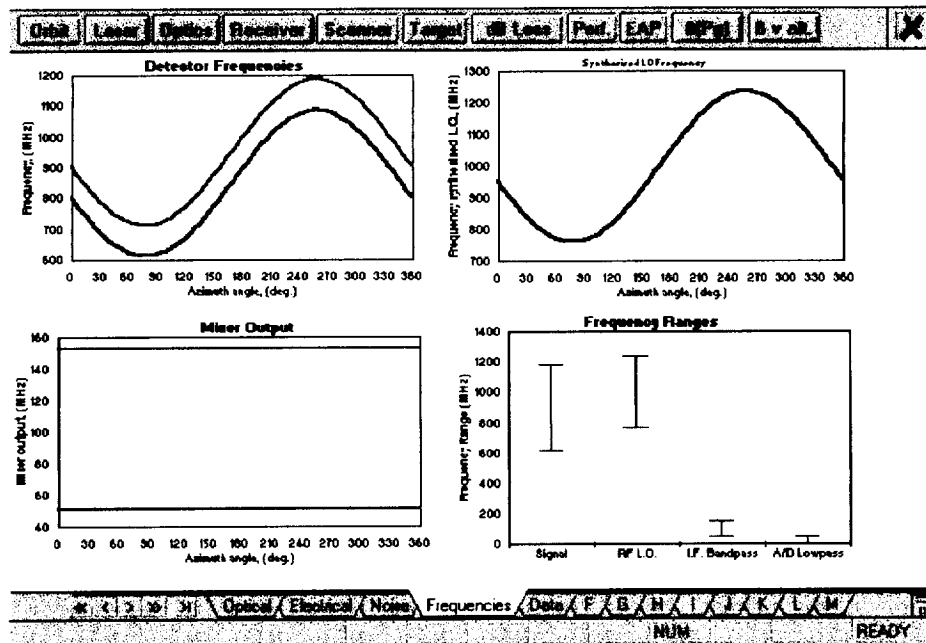
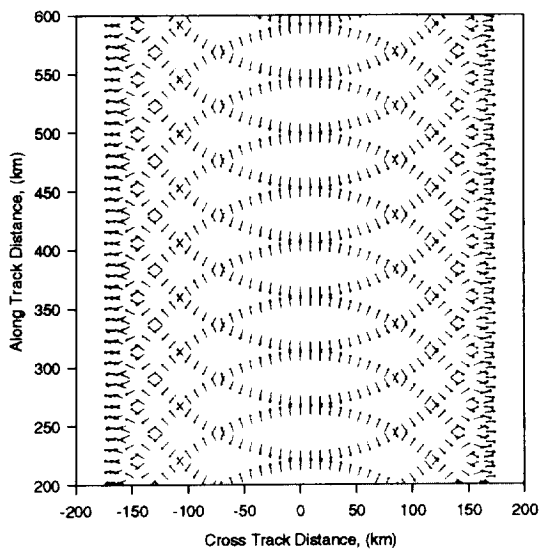


Figure (A.7) Plots of the minimum and maximum frequencies out of the detector (top left), the tuning curve for the electronic local oscillator (top right), the mixer output (bottom left) and the frequency bandwidths required in various stages of the receiver (bottom right).

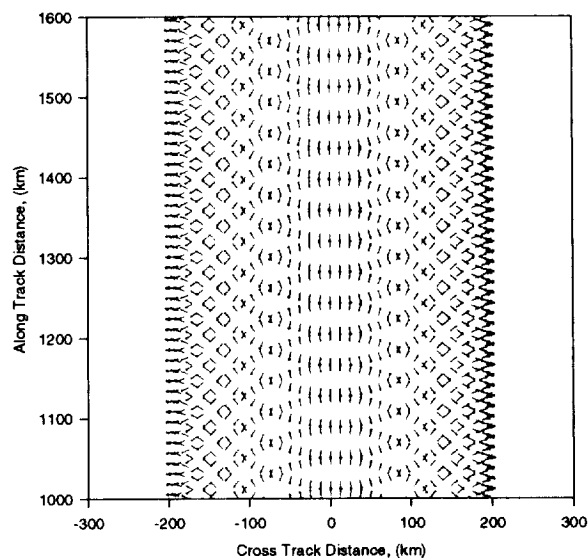
Orbit	Laser	Optics	Receiver	Scanner	Target	dB Loss	Pod	EAP	BPd	Avail.	X	
Wavelength						2.065479	µm					
Max. horizontal velocity						100	m/s					
Max. line of sight velocity (occurs at ground)						52.3543021	m/s					
Max. nadir error (any direction)						+/- 0.1	deg.					
Worst case line of sight velocity shift due to nadir error						12.3910204	m/s					
Max line of sight velocity allowing for nadir error						64.7453225	m/s					
Velocity bandwidth required to this point						129.460846	m/s					
Signal bandwidth required to this point						125.385584	MHz					
XMTR/LO frequency offset error						+/- 6	MHz					
Additional bandwidth to account for XMTR/LO offset error						10	MHz					
Total bandwidth required						135.385584	MHz					
Real/Complex receiver geometry						Complex						
Sampling rate over Nyquist						1.1	(1 = Nyquist, 2 = Twice as many samples as Nyquist)					
Sampling rate required/ channel						148.624142	Msamples/s					
No. bits						12	bits/sample					
pk. bits/s (one channel)						1.7871E+09	bits/s					
pk. bits/s (all channels)						3.5742E+09	bits/s					
Max altitude						20	km	nadir	No Error	31.4801 deg.	With Error	31.58608
Min altitude						0	km	nadir	31.5702 deg.		31.67665	
slant range margin						1	km					
slant range						24.4603473	km					
digitisation time						163.181872	µs					
bits/pulse						5832.42	bits/pulse					
ancillary words/pulse						20	words/pulse					
total bits/pulse						583462	bits/pulse					
PRF						10	Hz					
Bits/s averaged over one second						5834620	bits/s					
Orbit duration						5420.45249	s					
Data storage						3.1627E+10	bits/orbit					
						2.64E+09	words/orbit					
< > ⌂ Optics Electrical Notes Frequencies Data F G H I J K L M												
										NUM	READY	

Figure (A.8) Data requirements.

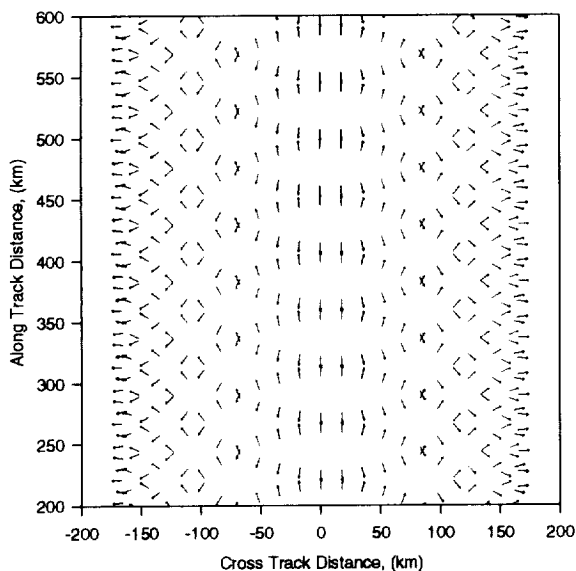
Appendix (A.I) Shot Patterns



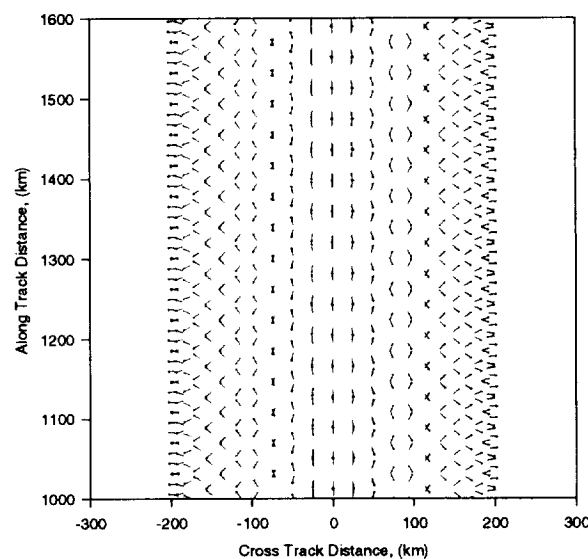
A) 300 km altitude, 10 rpm, 20 Hz PRF, 30 deg. nadir



B) 350 km altitude, 12 rpm, 20 Hz PRF, 30 deg. nadir



C) 300 km altitude, 10 rpm, 10 Hz PRF, 30 deg. nadir



D) 350 km altitude, 10 rpm, 10 Hz PRF, 30 deg. nadir

Figure (A.9) Shot density plots for both 10 Hz (bottom) and 20 Hz operation (top) at both 300 km altitude (left) and 350 km altitude (right). Each arrow is a line of sight vector pointing in the direction the shot was fired. Pairs of vectors that are close to each other but orthogonal in direction are considered to be most optimal for resolving the wind vectors. These vectors are represented by the green arrows while the red arrows represent vector pairs that have too little angular separation to be regarded as useful. It should be noted that the scanner rotation rate was adjusted slightly for each satellite altitude to improve the grouping of the vector pairs.